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Two-photon optical-beam-induced current microscopy of indium gallium nitride light emitting diodes

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ABSTRACT

In this study, epilayers of packaged indium gallium nitride light emitting diodes (LED's) are characterized by optical beam induced current (OBIC) and photoluminescence laser scanning microscopy through two-photon excitation. OBIC reveals spatial and electrical characteristics of LED's which can not be distinguished by photoluminescence. When compared with single-photon OBIC, two-photon OBIC imaging not only exhibits superior image quality but also reveals more clearly the characteristics of the epilayers that are being focused on. The uniformity of these LED's OBIC images can also be related to their light emitting efficiency.

Keywords: Indium gallium nitride, two-photon excitation, optical beam induced current, confocal microscopy, blue LED

1. INTRODUCTION

Optical beam induced current (OBIC) imaging is widely applied in the characterization of semiconductor based devices and integrated circuits, for instance, in failure analysis [1-3]. Conventionally, OBIC is performed through carrier generation by single-photon absorption. It has been shown that the effective point spread function (PSF) needs to be modified to account for the exponentially decaying optical field inside the material as a result of strong absorption[4,5]. When compared with photoluminescence imaging, OBIC imaging has the advantages of observing features that are more directly related to the electrical characteristics of semiconductor devices. The OBIC imaging of semiconductor devices has to meet the seemly contradictory conditions in that (a) the substrate or overlayers do not absorb or scatter the illuminating light strongly and (b) the photo-excited carriers are efficiently generated in the active layer. These requirements can be met if OBIC is performed with two-photon excitation[6] that employs wavelengths that are less than the bandgap photon energy, as demonstrated by Xu and Denk[7]. In this way absorption and scattering in the overlayers and substrate can be greatly reduced while carriers are effectively generated in the active layer.

In this report, we apply the two-photon OBIC technique to investigate indium gallium nitride (InGaN) based light emitting diodes (LED's) that have found wide spread applications in optoelectronics [8]. InGaN is considered to be the most important compound semiconductor among III-V nitride compounds because the InGaN enables light emitting through efficient carrier recombination[9]. One can obtain strong band-to-band emission from the green to the UV by varying the In content of InGaN. InGaN based LED's exhibit high external quantum efficiency and brightness and are the most viable blue LED's currently in use. It has been proposed that the emission is related to the presence of deep localized energy states that may originate from the In-rich regions which act as quantum dots[10-14]. However, the intensity distribution of LED's can exhibit poor spatial uniformity in active region, as can be seen under a microscope when LED's are forward biased. This poor spatial uniformity is associated with the fluctuation in In concentration and with the localized defects such as deficiency of nitrogen atoms in the lattice and threading dislocations. Imperfection in the electrodes would also affect the spatial uniformity of LED's.

We have found that two-photon excitation is effective in penetrating the packaging as well as the overlayers, such as *p*-doped GaN layers, or an *n*-doped GaN layer and sapphire substrate, if the laser beam is incident from the substrate side. The loss in two-photon excitation that is due to absorption and scattering is greatly reduced when compared with the loss in single-photon excitation. Absorption correction to the optical field inside the material is then not necessary[4-5]. In addition,

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the effect of spherical aberration when laser beam penetrates LED's plastic packaging is also reduced as a result of employing a longer wavelength. Therefore, two-photon OBIC imaging not only exhibits superior image quality but also reveals more clearly the characteristics of the epilayers focused on.

2. EXPERIMENTAL SETUP

2.1 Two-photon laser scanning microscopy

An inverted microscope and a galvano-mirror-based scanning system (Fluoview-IX70, Olympus) form the imaging platform. A mode-locked Ti:sapphire pulse laser (Tsunami, Spectra-Physics) pumped by a frequency doubled solid state laser (Millennia, Spectra-Physics) provides laser pulses of approximately 150 fs at 760 nm and 82 MHz for two-photon excitation, which is equivalent to 380 nm in excitation energy. A 740nm dichroic beam splitter is installed in the excitation path of the scanning unit to accommodate the coupling of the ultrafast laser pulses into the confocal microscope. The 488 nm line of a Kr-Ar laser is employed when single photon excitation is performed.

To avoid exceeding the response speed (10 KHz) of the current amplifier, the samples are scanned at a very slow rate of 157 sec/frame (150μs dwell time/pixel) at 1024x1024 pixels. A 40X (numerical aperture, 0.65) long working distance objective is employed for image acquisition. At focal point, the average power measured was 10 mW, therefore, the average energy exerted on the specimen for each pixel is approximately 1.5μJ (obtained by 150μs X 10 mW). On the other hand, considering the laser operating at 82 MHz with 150 fs pulse, when a NA=0.65 objective lens was used, the average and peak power densities at the focal point approximate 5×10^5 W/cm^2 and 4×10^{10} W/cm^2, respectively. We employ a very sensitive current amplifier (EG&G, model 181) of transimpedance as high as 10^9 V/A for photocurrent (PC) detection.

The total irradiated area is approximately 300μm x 300μm. The detected signal would correspond to photocurrent of a few nano-amperes. The two input channels in the scanning system detect the photoluminescence (PL) and the PC concurrently. The images are then reconstructed from the signals as a function of beam position. A schematic of this setup is shown in Fig. 1.

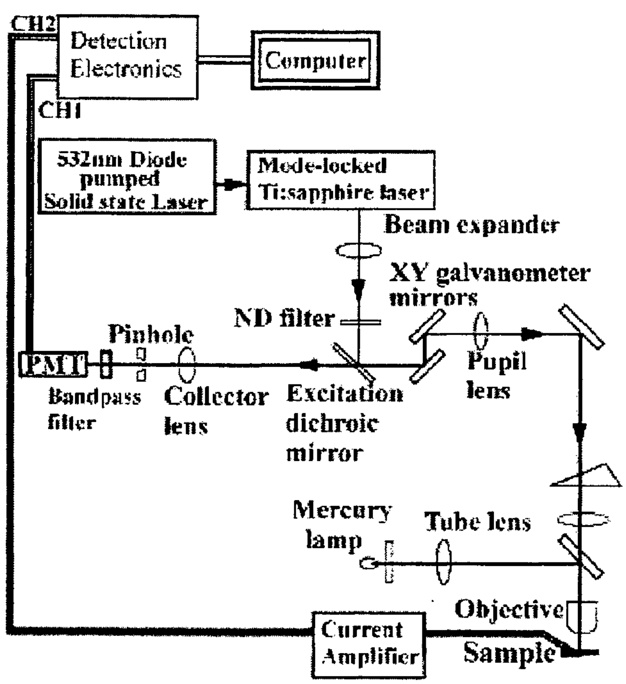


Figure 1. Schematics of the two-photon optical beam induced current and photoluminescence imaging system. The two input channels allow simultaneous acquisition of photocurrent and photoluminescence images.

2.2 InGaN LED's

The epilayers of GaN and InGaN are grown on top of a sapphire substrate. Since sapphire substrate is non-conducting, the two electrodes must be attached in the front side. There are two different brands of blue InGaN LED's being investigated in this study. One (Fig.2, LED A) has higher efficiency than the other (Fig. 2, LED B), as shown in their corresponding electro-luminescence spectra. Under the same driving current (0.5 mA), diode A emits brighter electro-luminescence than diode B. The diode samples observed are commercially available and have electro-luminescence that peaked around 475 nm with full width at half maximum (FWHM) bandwidth 35 nm, as shown in Fig. 2. Thinning, grinding, and polishing the packaging of the diodes allow direct observation and excitation under a microscope. We employ bandpass filters to select specific spectral bands for luminescence imaging.

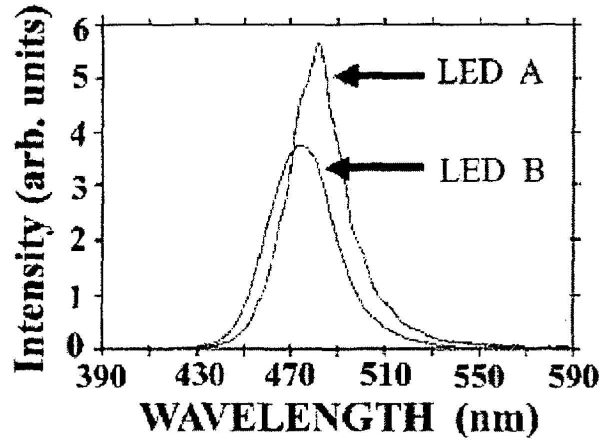
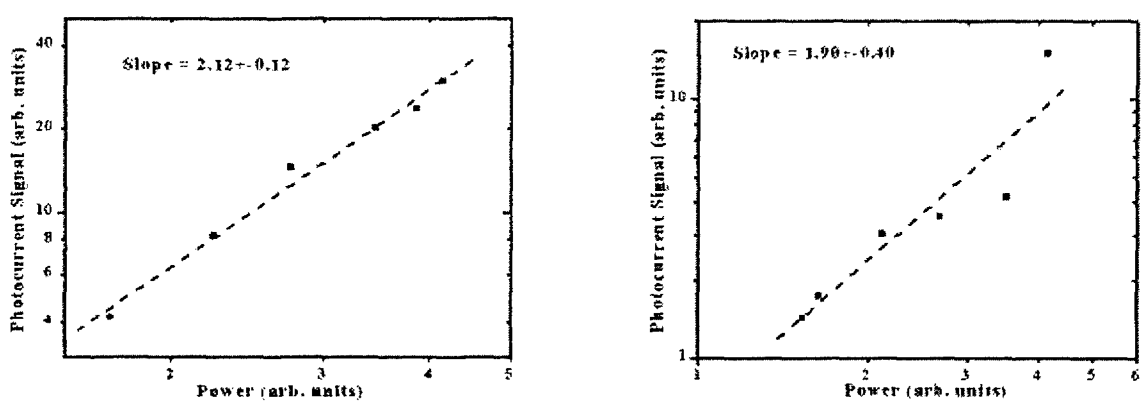


Figure 2. Electro-luminescence spectra of two different InGaN LED's.

3. RESULTS

Figures 3(a) and 3(b) show the power dependence of the PC signals from diode A and B, respectively. As expected for two-photon excitation, the slope values of 2.12 and 1.9 indicates the square dependence of such a nonlinear process.



(a) Diode A **(b) Diode B**

Figure 3. Photocurrent magnitude as a function of incident laser power for diode A(a) and B (b), respectively. The slope values are closed to 2, indicating two-photon excitation process is involved.

Two-photon PC and PL images of diode A are presented in Figs. 4(a) and 4(b), respectively. For comparison, the two-photon PC and PL images of diode B are presented in Figs. 4(c) and 4(d). The two electrodes are clearly shown in the PC images as one circular and one square dark region. They appear dark since there is no carrier generated underneath. The thin metallization layer is identified as the darker gray area that covers most of the active region shown in the PC image, whereas the bright strip in the edge shows the active region without thin metallization. In confocal PL imaging, fluorescence from the epilayers cannot be discriminated against that from the sapphire substrate spatially since the epilayers are thinner than the width of PSF in zaxis. In contrast, PC imaging would only detect a signal as a result of photocarrier generation. When compared with PL imaging, PC imaging has the advantages of being more specific and related to the diodes' electrical properties.

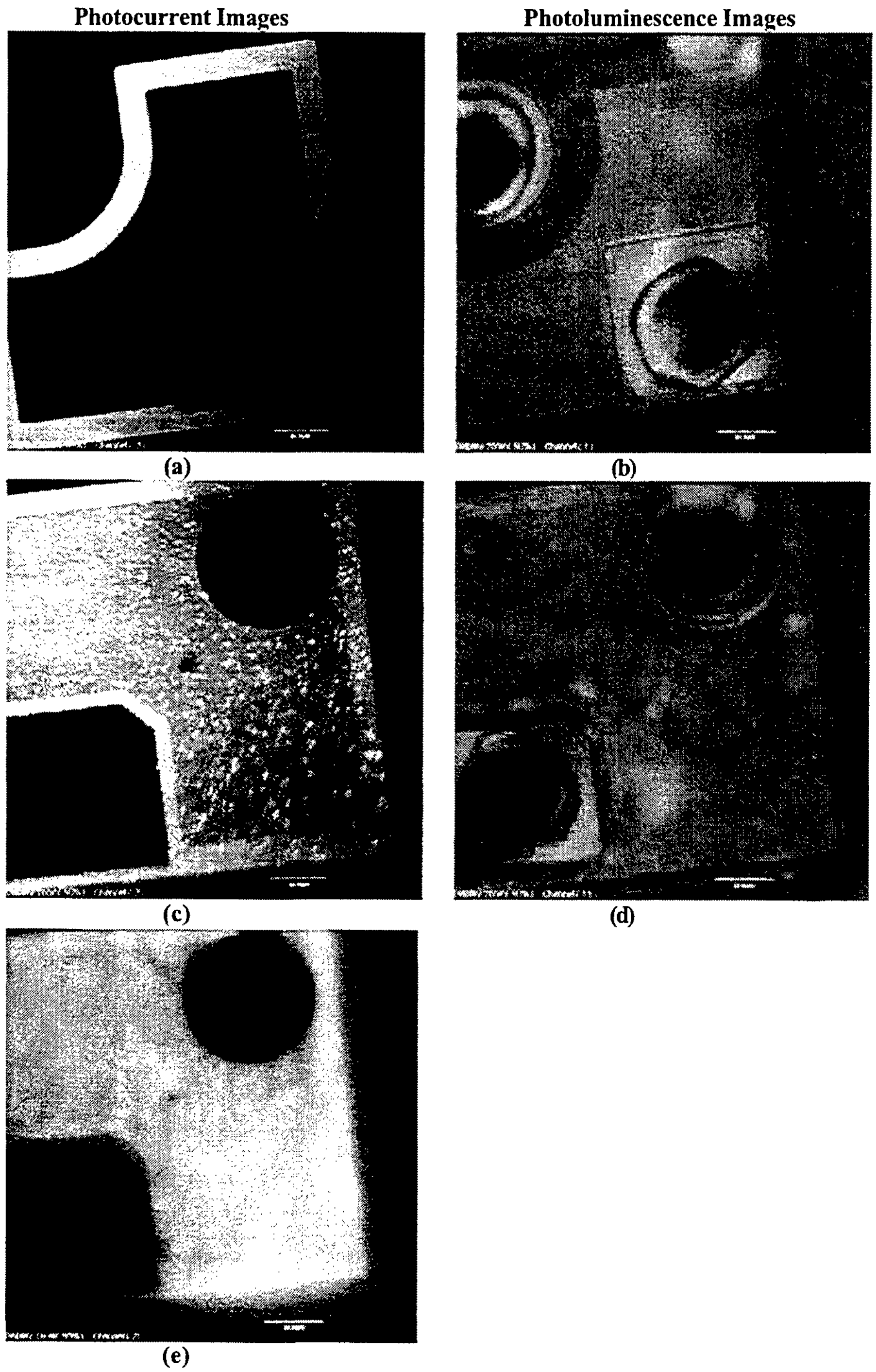
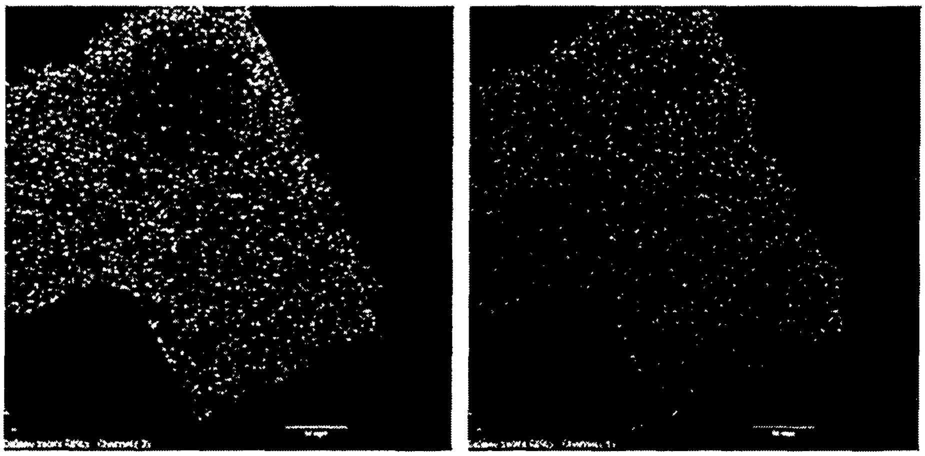


Figure 4. PC and PL images from diode A and diode B. (a) and (b) are two-photon PC and PL images from diode A, respectively. (c) and (d) are two-photon PC and PL images from diode B, respectively. In both (b) and (d) a bandpass filter

centered at 450 nm with 50 nm bandwidth is used in acquiring PL images. For comparison, one-photon PC image of diode B is shown in (e).

The most pronounced features in the PC image are the bright spots spread over the LED's in Fig. 4(c), which are a result of local variation in carrier transportation or generation efficiency. These spots have sizes ranging from 5 μm to less than the resolution of the objective used in our optical system, which is approximately 1.3 μm. The spots are similar to what have been observed in micro-spectroscopy of cathodoluminescence in InGaN quantum well devices[12]. Spots can also be found in the PL image, Fig. 4(d), which is acquired with a band pass filter of central wavelength 450 nm and bandwidth 50 nm. These spots do overlap with those found in the PC image, indicating that PC and PL have similar origin. However, the contrast in the PL image is less pronounced. According to Nakamura and co-workers[10-14], fluctuation in the In concentration will generate localized deep levels that greatly facilitate carrier recombination, and possibly carrier generation. Therefore PC may be a more sensitive indicator than PL in detecting local variation in the active region. For comparison, Diode A did not exhibit the spots as in Diode B, as shown in Figure 4 (a) and 4 (b). The advantage of two-photon excitation is further clarified by comparing the PC image obtained through single photon excitation shown in Fig. 4(e). The 488 nm line of an argon-krypton mixed gas laser is employed for single photon excitation. The image appears blurred with reduced contrast and no detailed features can be observed.



(a) (b)

Figure 5. PC (a) and PL (b) images from an unpackaged diode with heavy indium doping.

To observe the effects of heavy indium doping, the PC and PL images of an unpackaged InGaN diode are shown in Fig. 5(a) and (b), respectively. The color of electro-luminescence from this diode is green. In contrast with PC images shown in Fig. 4, there is PC signal coming out of one of the electrodes, as shown in Fig. 5(a). Unlike a packaged diode in which scanning beam must irradiate from the side of electrodes, in this case the scanning laser beam can penetrates the sapphire substrate during imaging. The weaker magnitude of PC signal within the circular electrode indicates that there is an insulation layer under the electrode to homogenize the current distribution over the diode. High indium concentration was expected to generate greater inhomogeneity within the active layer and this inhomogeneity is manifested in Fig. 5.

4. DISCUSSION

4.1 Two-photon excitation

Optically the advantages of two-photon OBIC over single-photon OBIC can be summarized as (1) deeper penetration, (2) less distortion to field distribution or PSF, and (3) less spherical aberration[15]. Absorption in the top epilayer can be minimized by using a excitation wavelength that is below bandgap photon energy. Deeper penetration would then result because of reduced absorption. Regarding the image formation of OBIC, detailed model for 1-photon OBIC has been developed by Wilson *et al*[4,5], in which a semi-infinite piece of semiconductior is considered. Within the model, a specific PSF that takes into account substrate absorption is introduced. It is found that the resolution is not limited by the carrier diffusion length and the optimum focus position in terms of the maximum number of carriers generated is a few optical units below the surface. In the case of single-photon OBIC, it would then be more difficult to perform conventional deconvolution calculation to improve image quality since the PSF is distorted as a result of absorption. In contrast, two-photon OBIC would open the possibility for image deconvolution. The reduction of spherical aberration is expected since the magnitude of it is proportional to the path length difference in the optical imaging system and inversely proportional to wavelength, *i.e.* $\Delta\phi \propto \frac{\Delta L}{\lambda}$. Employing a longer wavelength would naturally result in smaller spherical aberration. However, two-photon OBIC may present the following problems. Most significantly, at high excitation intensity, multi-photon effects may damage the LED's.

4.2 InGaN LED's

Efficient light emission of a blue LED is related to deep localized energy states formed in the In-rich regions acting as quantum dots in the InGaN layer. These states may also be the origin of photocurrent. Since the direct band gap (~3.4 eV) of intrinsic GaN is much higher than that of InGaN, it is less probable that the wavelength we used would excite carriers over GaN's band gap. According to Nakamura and Fasol[8], though the PL spectra of p-doped GaN and InGaN overlap each other, the PL intensity from InGaN is higher by more than an order of magnitude. It is likely that most photo-generated carriers are generated in the InGaN layer. In OBIC, the detected signal can be regarded as the convolution of carrier generation and transportation to the electrodes. Owing to the LED's planar structure and the relatively low resistance in the p-dope and n-doped layers, the overall carrier transportation efficiency should present little variation over the LED's plane. Therefore, the spots observed in Fig. 4(a) may reflect local variation of carrier generation efficiency in the active layer. This variation may also be caused by changes in indium compositions. The higher contrast in the PC image than the PL image indicates that PC is more sensitive to local variation in carrier generation. For the two InGaN light emitting diodes. Their light emitting quality and efficiency are reflected in the PC images. In particular, as indium concentration increases, the inhomogeneity observed in the active layer also increases.

5. CONCLUSIONS

In conclusion, we have demonstrated the characterization of the InGaN based LED's through two-photon OBIC laser scanning microscopy[16]. However, one needs to be careful about damages induced by nonlinear optical excitation. Compared with single-photon excitation, two-photon excitation clearly exhibits better spatial resolution and reveals some interesting features not found before. Optoelectronic devices are of multilayered heterostructure with active layers buried in the middle. Two-photon excitation is more effective than one-photon excitation in reaching the active layers of these devices. Specifically, PC is more sensitive and specific than PL in showing their characteristics.

ACKNOWLEDGEMENT

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